

 **Cosmic Chemical Evolution**  
(St. Michaels, June 2010)



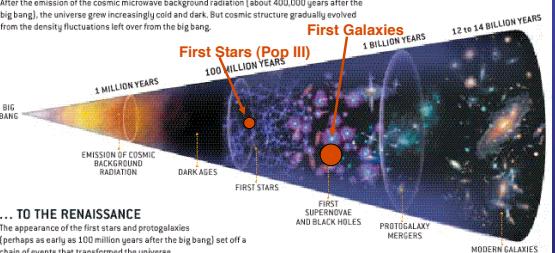
## The Formation of the First Stars

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**From the Dark Ages to the Cosmic Renaissance**

**FROM THE DARK AGES ...**  
After the emission of the cosmic microwave background radiation [about 400,000 years after the big bang], the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.



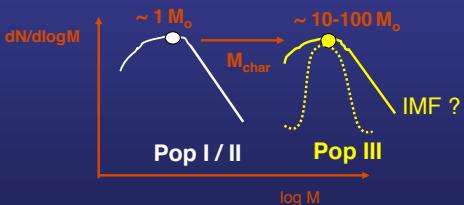
**... TO THE RENAISSANCE**  
The appearance of the first stars and protogalaxies [perhaps as early as 100 million years after the big bang] set off a chain of events that transformed the universe.

(Larson & Bromm, *Scientific American*)

- First Stars — Transition from Simplicity to Complexity

**The First Stars: The “Standard” Model**

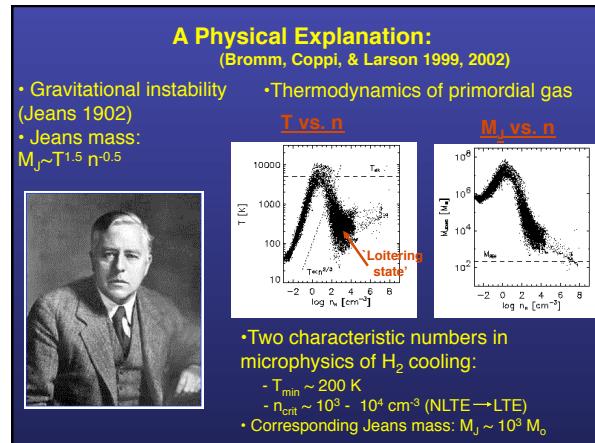
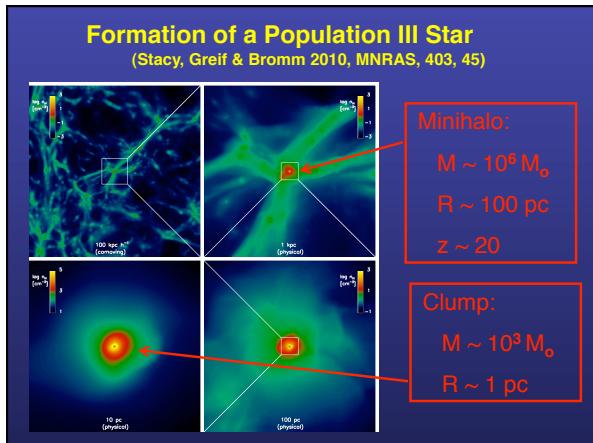
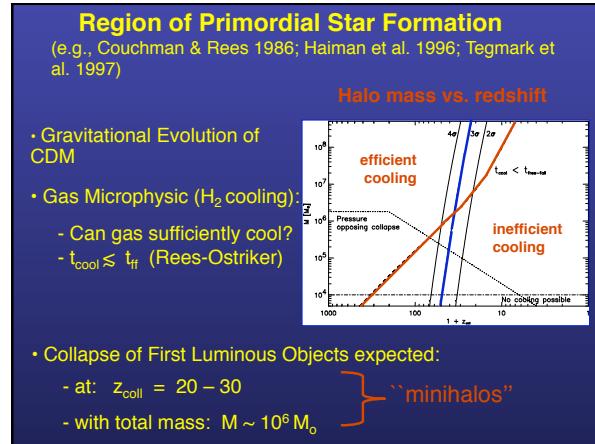
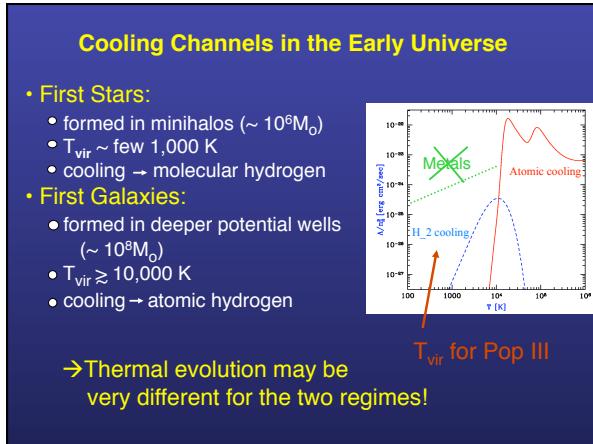
- Numerical simulations
  - Bromm, Coppi, & Larson (1999, 2002)
  - Abel, Bryan, & Norman (2000, 2002)
  - Nakamura & Umemura (2001, 2002)
  - Yoshida et al. (2006); O’Shea & Norman (2007); Gao et al. (2007); Yoshida et al. (2008)
- Main Result: →**Top-heavy initial mass function (IMF)**

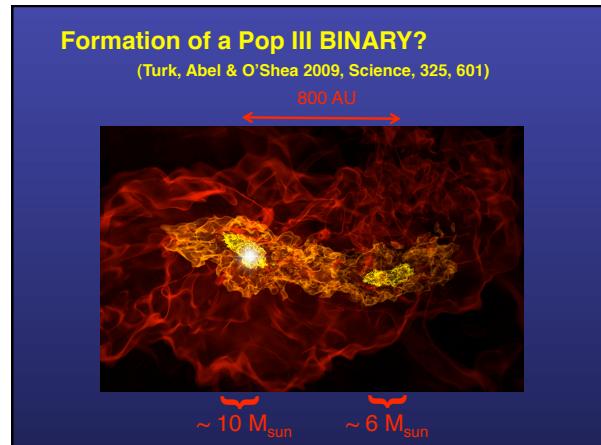
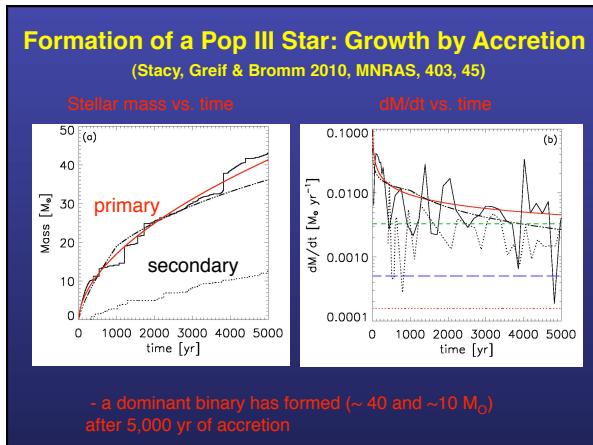
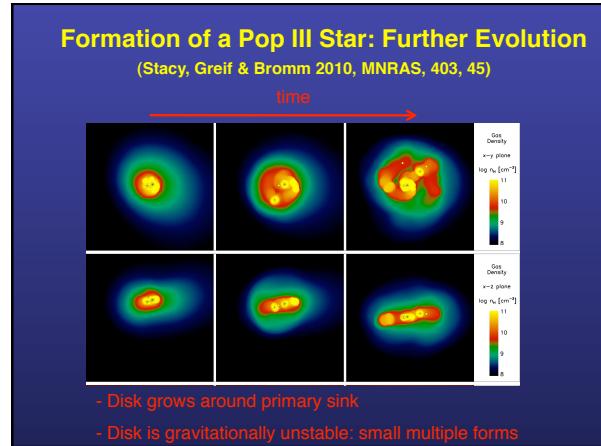
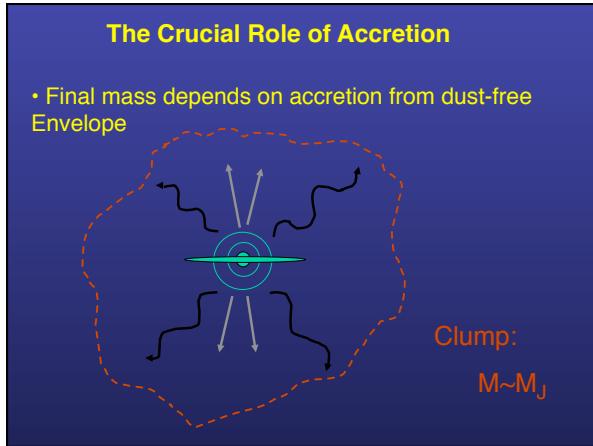


The graph plots the differential mass function  $dN/d\log M$  against the logarithm of mass  $\log M$ . It shows two distinct populations: Pop I/II (left) with a peak around  $\sim 1 M_\odot$  and a characteristic mass  $M_{\text{char}}$ , and Pop III (right) with a peak around  $\sim 10-100 M_\odot$ . A dashed line labeled "IMF ?" represents a theoretical model.

**Character of Population III Star Formation**

- Simplified physics
  - No magnetic fields yet (?)
  - No metals → no dust
  - Initial conditions given by  $\Lambda$ CDM  
→ Well-posed problem
- First Stars = Cold dark matter (CDM)
  - + atomic and molecular physics of H/D/He

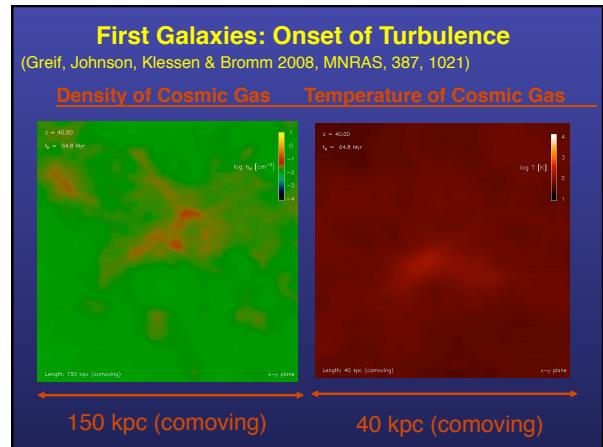
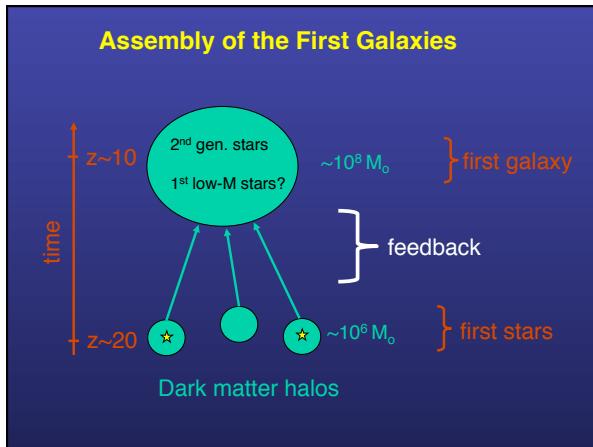
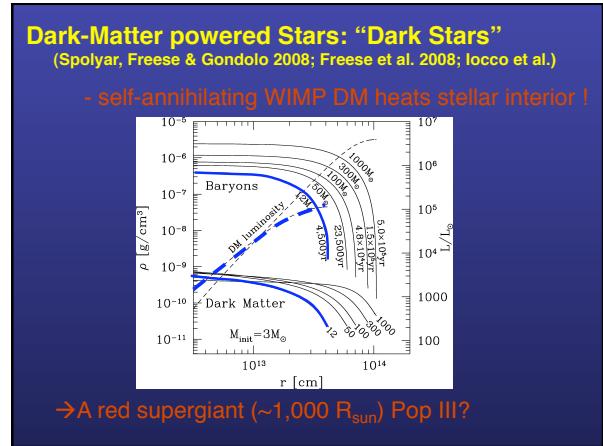


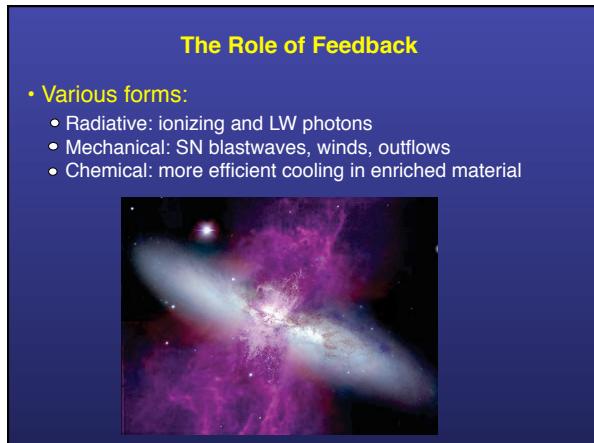
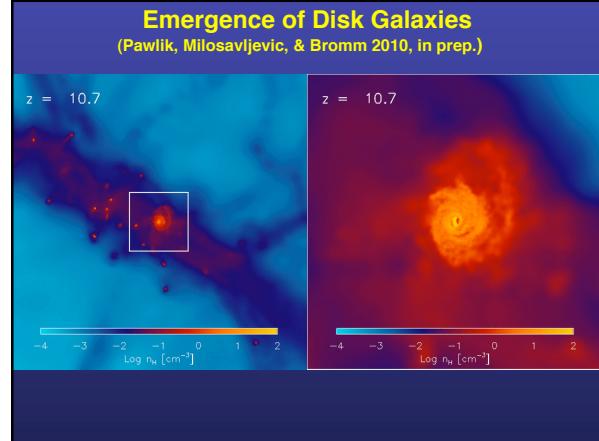
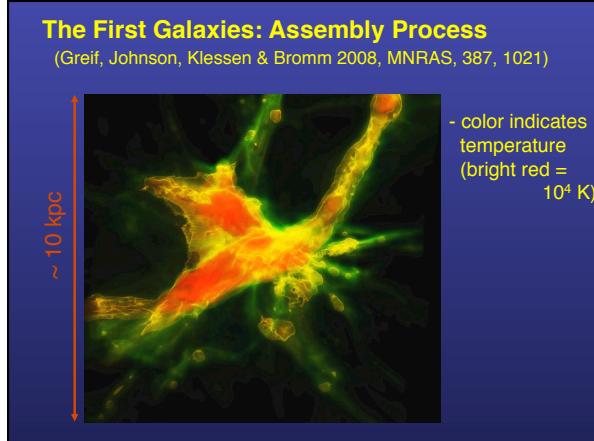


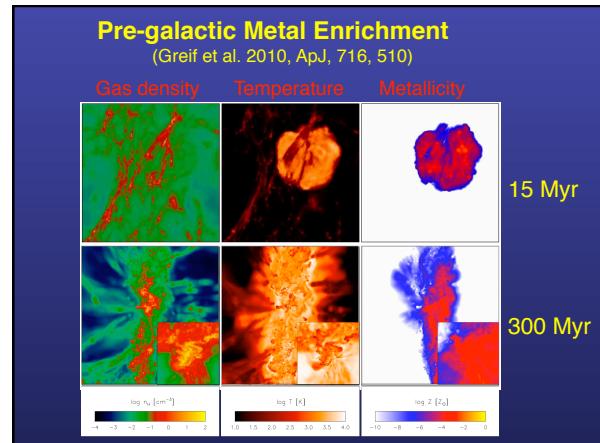
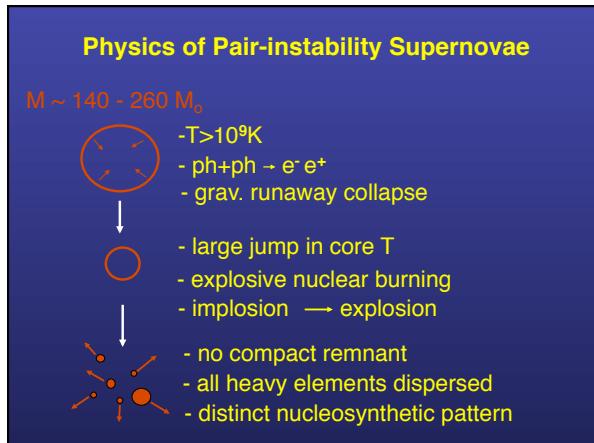
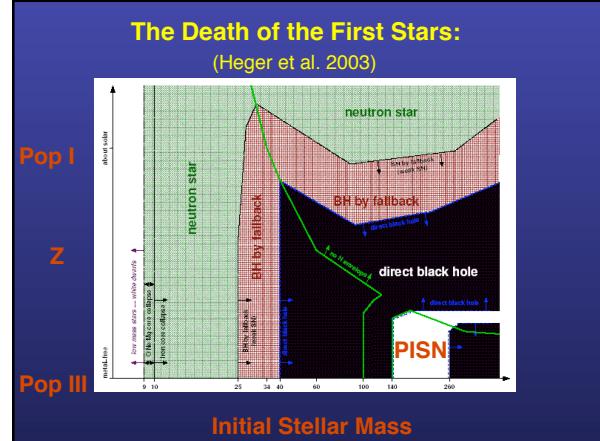
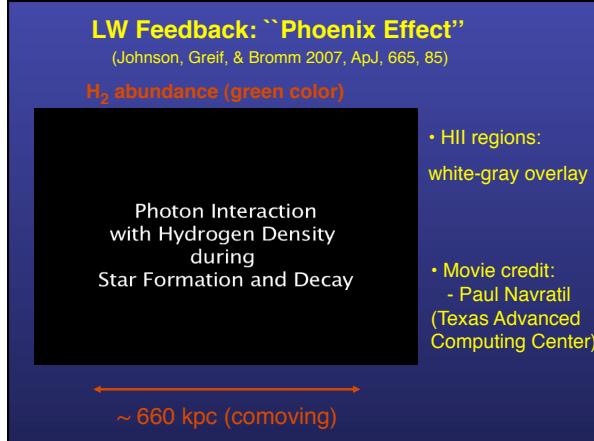
### Neglected Processes

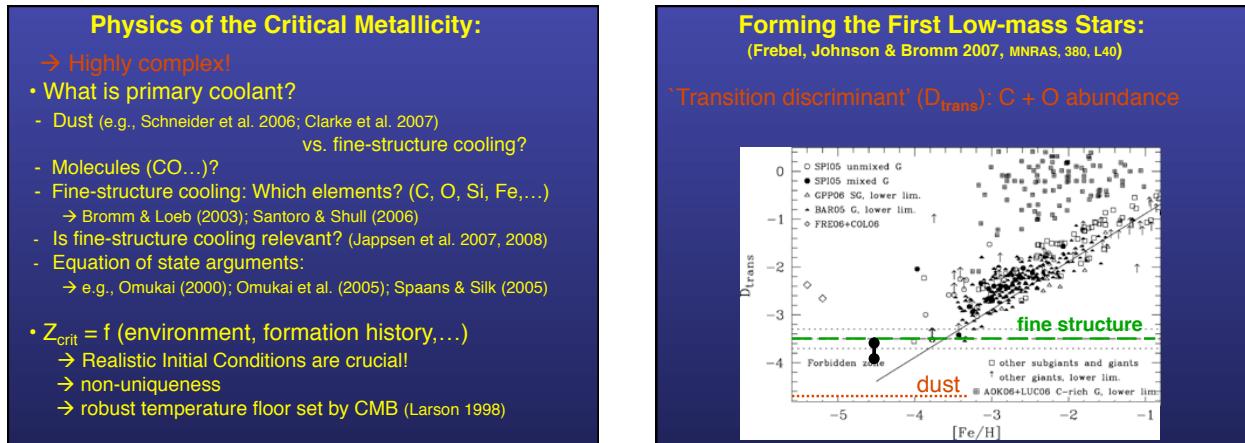
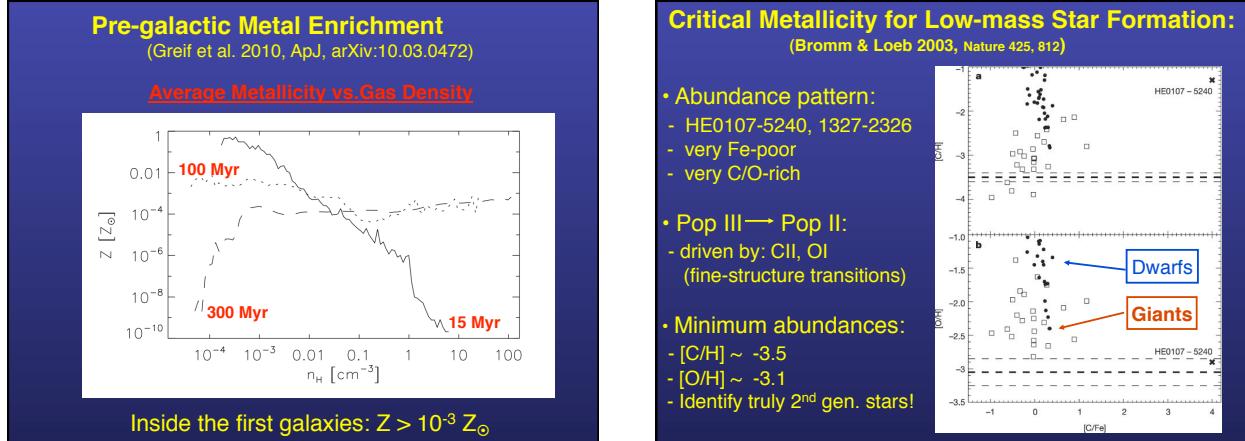
- Magnetic fields (MHD effects, MRI, dynamos, jets...)
  - E.g., Tan & Blackman 2004; Machida et al. 2006; Silk & Langer 2006
- Cosmic Rays (ionization, heating, chemistry...)
  - E.g. Shchekinov & Vasiliev 2004; Rollinde et al. 2005, 2006; Jasche et al. 2007; Stacy & Bromm 2007

→ might lead to lower Pop III masses!
- Possible modifications to CDM (WDM, annihilation heating...)
  - E.g. Yoshida et al. 2003, Gao & Theuns 2007; Spolyar et al. 2008





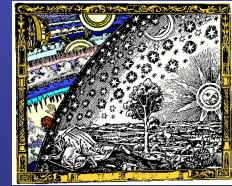




## Summary

- Primordial gas typically attains:
  - $T \sim 200 - 300$  K
  - $n \sim 10^3 - 10^4$  cm $^{-3}$
- Corresponding Jeans mass:  $M_J \sim 10^3 M_\odot$
- Pop III SF might have favored *very massive stars*
- Transition to Pop II driven by presence of metals ( $z_{\text{trans}} \sim 15 \pm 5$ )
- PISNe completely disrupt mini-halos and enriches surroundings
- First galaxies were already metal-enriched!

## Perspectives:

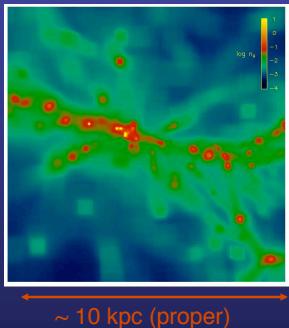


- Very dynamic, rapidly developing field
- Closing the final gap in our worldview
- Driven by supercomputers and our best telescopes
- The high-redshift frontier: How did it all begin?

## Feedback: LW background delays SF

(Johnson, Greif, & Bromm 2008, MNRAS, 388, 26)

### H number density



- with  $J_{\text{LW}} = 0.04 \times 10^{-21}$   
erg s $^{-1}$  cm $^{-2}$  Hz $^{-1}$  sr $^{-1}$
- present:  
→ Only allow 4 Pop III stars to form (out of 10 possible)!